Cooperative Adaptive Cruise Control Human Factors Study: Experiment 2—Merging Behavior

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FOREWORD

This report presents human factors experimental results from an examination of the effects of cooperative adaptive cruise control (CACC) on driver performance in a variety of situations. The experiment was conducted in a driving simulator using a scenario in which the driver was required to enter into a stream of vehicles. CACC is envisioned as an automated vehicle application that complements the capabilities of the vehicle operator without degrading the vehicle operator's alertness and attention.

This task was completed with and without speed assistance during the merge. Merging maneuvers with the CACC system successfully reduced workload and eliminated collisions during merges. Drivers who were required to manually control speed and enter a continuous flow of traffic experienced a significant number of crashes, which indicated that drivers' merging maneuvers are highly sensitive to the behavior of other drivers and to merging distances.

This report informs the discussion among transportation professionals about how automated vehicle applications will be embraced by everyday drivers. The experiment results should be useful to researchers and transportation professionals interested in the effects of automation on driver behavior.

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Research and Development

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16. Abstract

This study is the second in a series of four experiments exploring human factors issues associated with the introduction of cooperative adaptive cruise control (CACC). Specifically, this study explored drivers' abilities to merge into a stream of continuously moving vehicles in a dedicated lane. Participants were asked to complete one of three different types of merges in the Federal Highway Administration Highway Driving Simulator:

- Merge with non-CACC vehicle into a left dedicated lane without CACC platooning and varying vehicle gaps.
- Merge with CACC vehicle into the middle of a CACC platoon or continuous stream of vehicles without speed assistance.
- Merge with CACC vehicle into a CACC platoon with longitudinal speed assistance.

As measured by the National Aeronautics and Space Administration Task Load Index, drivers' perceived workload was significantly less for both groups that drove with the CACC system engaged than for the group that was required to manually maintain speed the entire drive. Perhaps surprisingly, participant condition did not significantly affect physiological arousal as assessed by galvanic skin response (GSR). However, across all groups, GSR was significantly greater during the merges than during cruising/straight highway driving time periods.

The participants who drove with the CACC system during the merges (as defined by the operation of the system) did not experience any collisions. Both groups that were required to manually adjust speed to merge into the platoon of vehicles experienced collisions in 24 (18 percent) of the merges, suggesting that some gaps may be too small for drivers to merge into at high speeds. An alternative explanation, supported by participant feedback, is that drivers expect others to act in a courteous manner and to create larger gaps for entrance onto a freeway—something that may not be possible in real-world CACC deployment.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS

ACC	adaptive cruise control
CACC	cooperative adaptive cruise control
FHWA	Federal Highway Administration
GEE	generalized estimating equation
GSR	galvanic skin response
HOV	high-occupancy vehicle
NASA-TLX	National Aeronautics and Space Administration Task Load Index
ROI	region of interest
SSQ	simulator sickness questionnaire
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle

CHAPTER 1. INTRODUCTION

This report describes the second experiment in a series of four that explore cooperative adaptive cruise control (CACC). CACC combines three driver assist systems: (1) conventional cruise control, which automatically maintains the speed a driver has set, (2) adaptive cruise control (ACC), which uses radar or light detection and ranging sensors to automatically maintain a gap the driver has selected between the driver's vehicle and a slower moving vehicle ahead, and (3) dedicated short-range communications to transmit and receive data with surrounding vehicles so that the cruise control system can more quickly respond to changes and speed and location of other CACC vehicles, including vehicles that the driver cannot see.(1)

When using CACC, drivers share vehicle control with an automated system that includes vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. Communications between nearby CACC-equipped vehicles will enable automated coordination and adjustment of longitudinal control through throttle and brake activations. Automated control should enable CACC-equipped vehicles to safely travel with smaller gaps between vehicles than drivers could safely manage on their own. Smaller gaps should subsequently increase the roadway capacity without increasing the physical amount of roadway.

The viability of CACC as a successful and widely used technology is dependent on many factors. One of these factors is the ability of drivers to enter and exit streams of CACC platoons. The manner in which drivers enter the CACC platoons relies on the relationship between CACC traffic flow and other non-equipped CACC vehicles. It is believed that, at minimum, in the early stages of CACC market penetration, there will be a dedicated CACC lane. The lanes would function much like high-occupancy vehicle (HOV) or express lanes operate; drivers would only be allowed to travel in the dedicated lane if certain requirements were met. In that case, the drivers would have to be using CACC-equipped vehicles. These lanes would presumably have some sort of physical separation from the regular flow of traffic. This would prevent the disruption of the CACC flow due to non-CACC-equipped vehicles attempting to enter the traffic stream.

This study is the second in this series of four CACC experiments and explores the ability of drivers to enter and exit dedicated CACC platoon lanes. The goal of this research is to address some of the critical human factors issues for CACC usage related to the abilities and limitations of the drivers using the system. Specifically, the goals of this experiment are to (1) investigate drivers' abilities to successfully enter a dedicated CACC lane and join an already established vehicle platoon and (2) assess the workload associated with this maneuver.

There are many ways in which CACC can be implemented in the real world, and this study makes several critical assumptions both in terms of vehicle technology and roadway infrastructure. The assumptions made here should not imply that the CACC system will ultimately be implemented in exactly this manner. Rather, they serve as points of reference for addressing potential human factors issues.

The first assumption is based on whether CACC systems will primarily function as V2V or V2I systems. A V2I system implies that platoons will have some external control from a centralized source (or sources). A V2V system, however, implies that CACC platooning vehicles will act in a selfish way. In a CACC system platoon, there are two primary ways in which a driver can enter the platoon in a location other than the front or rear (i.e., the first car or the last vehicle in a platoon). The first way involves requesting permission to move into the platoon (a system that is at least partially reliant on V2I communications). In this case, a driver notes a platoon of CACC vehicles that he or she would like to join. The driver requests permission, permission is granted, a larger gap is provided between two of the platooned vehicles, and the driver is able to enter the platoon. This method adds complexity to the CACC operating system and driver interface.

The second manner in which a driver can enter a CACC platoon is one in which vehicles act selfishly (a primarily V2V reliant system). That is, vehicles will communicate locally with nearby vehicles, and vehicle actions will serve the driver, rather than the drivers nearby. Vehicles will act to maintain personal gaps and speed. This can present an issue when a driver attempts to enter a CACC platoon. Because CACC vehicles will act in a selfish manner, a vehicle will not request entry into a platoon, and an extra gap for that vehicle will not be created. Instead, the driver will merge into the platoon, and the other vehicles in the platoon will adjust speed to restore the desired gap between vehicles and to accommodate the new platoon member. This method results in a variety of human factors issues, especially when vehicles are traveling with short gap distances.

However, a primarily V2V-based system can work from an algorithm that allows vehicles to work cooperatively and selfishly simultaneously. In the case of joining a platoon, the principle vehicle may be able to communicate with already platooning vehicles. The system can then identify the needed speed to enter the platoon, ultimately assuming lateral and longitudinal control of the principle merging vehicle. This is especially important if platoons are travelling with smaller gaps. Shorter gaps between vehicles can increase traffic throughput and ultimately reduce congestion related roadway delays. However, shorter following gaps lead to problematic human factors issues.

At 104.6 km/h (65 mi/h), a 1-s gap leaves approximately 28.96 m (95 ft) between vehicles. Previous studies have shown that drivers feel both comfortable and safe travelling at gaps shorter than 1 s. For example, in an on-road study testing drivers' choices in following distances, drivers regularly used gap settings shorter than 1 s. In fact, overall, when following another vehicle, drivers elected to set the gap at 0.7 or 0.6 s 8 percent of the time.(2) However, with a 0.6-s gap, there is approximately only 17.37 m (57 ft) between vehicles. If an average vehicle length is assumed to be around 6.10 m (20 ft), this leaves less than 5.64 m (18.5 ft) of buffer on either direction for a merging vehicle. As a result, at these shorter distances, drivers may not feel comfortable or have the skill to join the platoon without longitudinal assistance. Similarly, drivers may not feel comfortable allowing the system to assume longitudinal control during a merge. For this reason, driver acceptance of longitudinal acceleration by the CACC system to join a platoon will be explored.

Another very important assumption made in this study is that the CACC system will require dedicated infrastructure in its early implementation. This infrastructure requires that the CACC lane (or lanes) are physically separated from "normal" travel. This is important for several reasons. CACC will be of the most use in congested regions. This congestion often leads to lower travelling speeds and a great deal of speed variation (i.e., stop-and-go or slow-and-go traffic). Because CACC-equipped vehicles travelling in a separate lane will travel at fairly constant speeds with standard gap distances, the lane will be less susceptible to speed variability. As a result, vehicles in the CACC lane are likely to be travelling at speeds greater than the normal travel lanes. The speed differential between the two types of lanes will introduce problems reaching speeds great enough to transfer from one type of lane to the other. Instead, drivers will be required to enter the lane from a separate on ramp (much like drivers entering and exiting dedicated HOV lanes). The physical separation between the two types of lanes also prevents non-CACC-equipped vehicles from entering the CACC lane and disrupting travel flow stability.

Given these assumptions, there are many human factors issues that arise with merging with CACC platoons. This experiment will explore the following three different types of merges:

- Merging with non-CACC vehicle into a left dedicated lane without CACC platooning and varying vehicle gaps.
- Merging with CACC vehicle into the middle of a CACC platoon or a continuous stream of vehicles without speed assistance.
- Merging CACC vehicle into a CACC platoon with longitudinal speed assistance.

CHAPTER 2. METHOD

In this chapter, an overview of the approach to assessing workload, arousal, and merging behavior is described before providing more extensive details on the experimental design and procedures.

APPROACH

Three groups drove the same stretch of simulated limited access roadway. This was the same simulated roadway used in experiments 1 and 3. All groups were asked to exit and enter the roadway four times. The first group completed this task with no cruise control. The second group used CACC while travelling in the main roadway stream but was required to adjust the vehicle speed when entering and exiting the CACC stream. The third group was provided with CACC that controlled speed both while in the travel lane and while using the entrance and exit ramps.

Workload Assessment

Driver workload was assessed by administration of the National Aeronautics and Space Administration Task Load Index (NASA-TLX) and was measured four times.(3) The first assessment was during a practice drive and was intended to accustom participants to providing verbal response to the NASA-TLX protocol. The second workload administration was approximately 9.33 km (5.8 mi) into the drive, immediately after the first complete exit and reentrance to the main travel lane. The second NASA-TLX administration was intended to assess the workload imposed by a merge into traffic. The third assessment was 32.19 km (20 mi) into the drive and was intended to assess the workload associated with driving in a stable, unchanging state (i.e., a baseline index). At this point, drivers were between merging events and were likely to feel comfortable with the driving task in general. The fourth and final NASA-TLX was administered immediately after the final merging event, approximately 37.02 km (23 mi) into the drive. The final workload assessment was intended to assess the workload change that may occur over time with practice merging.

Physiological Arousal

Physiological arousal was assessed by measuring eyelid closure, pupil diameter, and skin conductance. These measures were assessed at eight different 15-s periods during the drive. Four of these periods were immediately before exiting the roadway (cruise periods), and four were in the last portion of the merge events.

Merging Behavior

At exits 4, 8, 12, and 16, participants were asked to leave the CACC platoon by using a left exit ramp and then reenter traffic using a left on-ramp. Exits were approximately 2.33 km (1.45 mi) apart. Traffic was continuous and did not stop, which forced participants to enter mid-stream and not at the beginning or end of a platoon. The two groups with CACC were required to join a platoon of vehicles with a constant 1.1-s gap. The group with CACC merge assistance was not required to adjust speed in any way. The system longitudinally controlled the entire drive without failure. However, if the participant pressed the brake, the system did disengage. The group without CACC merge assistance was required to manage and adjust their own vehicle speed to appropriately enter the platoon gap. The third group, which drove without CACC, maintained longitudinal and lateral control of the vehicle. This group was provided with a variety of gap sizes to merge into, which was hoped to help determine whether participants generally prefer a shorter or longer gap distances or whether no preference is given (i.e., drivers will accept the gap presented).

Equipment and Materials

The Driving Simulator

The experiment was conducted in the Federal Highway Administration (FHWA) Highway Driving Simulator. The simulator's screen consists of a 200-degree portion of a cylinder with a radius of 2.7 m (8.9 ft). Directly in front of the driver, the design eye point of the simulator is 3 m (9.5 ft) from the screen. The stimuli were projected onto the screen by 3 projectors with resolutions of 2,048 horizontal by 1,536 vertical pixels. Participants sat in a compact sedan. The simulator's 6-degrees of freedom motion base was enabled. The typical motion for roll, pitch, and yaw fell within ±4 degrees.

The simulated vehicle was equipped with a hidden intercom system that enabled communications between the participant and a researcher who ran the experiment from a control room. The researcher in the control room could also view the face video from the eye-tracking system and monitor the participants' well-being.

Eye-Tracking System

The same eye tracking system used in the first in this series of four experiments was used in the present experiment. Gaze direction accuracy varied by participant. For the left eye, the mean accuracy of gaze position across all participants was 1.4 degrees (radius) with a 0.69-degree standard deviation. For the right eye, the mean accuracy was 1.2 degrees with a 0.94-degree standard deviation. In this study, the eye-tracking system was primarily used to determine whether participant glance behavior varied systematically based on experimental condition. The following display locations were tracked:

- Multifunction touchscreen display that hosted either the CACC user interface.
- Instrument panel (with speedometer and tachometer).
- Rearview mirror.
- Left-side mirror.
- Right-side mirror.
- Out the windshield (projection screen).
- Right side of the wrap around screen (blind spot area).

In addition to tracking the direction of gaze, the eye-tracking system computed eyelid opening and pupil diameter. These measures were also recorded at 120 Hz.

Multifunction Display

Similar to the other three experiments in this series, a 17.78-cm (7-inch) liquid crystal display touchscreen display was mounted on the center console above the radio. For the two conditions that used the touchscreen, it displayed the set speed (always set to 112.65 km/h (70 mi/h)), the set following distance (always set to near), and the status of the CACC system (engaged or not engaged). The engage button on the right side of the display could be used by the participants to engage CACC. When the system was engaged, the text and icons appeared green; when the system was not engaged, the text and icons appeared red.

For the control group, the multifunction display was turned off. The control condition was not given any specific directions in terms of following distance other than to drive as they normally would.

Skin Conductance Sensor

As in experiment 1, galvanic skin response (GSR) was measured with silver-chloride salt electrodes placed on the palmar-side base of two fingers on the participant's left hand. The electrodes were connected to a small sensor with a Bluetooth® transmitter strapped to the left wrist.

The Simulation Scenarios

Participants drove in a dedicated center lane on a simulated eight-lane interstate highway (four lanes in each direction). The roadway was the same used in experiment 1 with a few minor variations. The entrance to the center dedicated lane was accessed from the left side of the roadway from a ramp. The simulation began with the participant's vehicle as the third in the CACC platoon queue. Once the participant was ready to begin, the two vehicles in front of the participant accelerated and merged into the CACC lane and cruised at 112.65 km/h (70 mi/h). The two groups that drove with CACC engaged the system, and the participant's vehicle maintained a 1.1-s gap between it and the vehicle in front of it. The control group participants could follow at any distance they chose.

In total, there were 18 exit ramps, each placed approximately 2.33 km (1.45 mi) apart. Participants were asked to use exits 4, 8, 12, and 16. Exit ramps to the left of the main travel path that were not used by the participants were blocked by traffic barrels. This was intended to serve as a reminder to participants as to which exit ramps to use. Additionally, no traffic to the right of the barrier was present.

Calibration of CACC Vehicle Size

In experiment 1, the vehicle size was scaled down so participants could accurately perceive the correct following distance. This same vehicle scaling was used in experiment 2.

Procedure

Upon arrival at the research center, participants were asked to review and sign an informed consent statement. This was followed by the health screening to ensure that the participants were not at an increased risk of simulator sickness as a result of illness or lack of sleep. Participants were asked to show a valid driver's license. A Bailey-Lovie eye chart was used to verify a minimum of 6/12 (20/40) visual acuity with correction if necessary. A slideshow presentation was shown to all participants. The presentation provided an overview of the experimental instructions and familiarized participants with the NASA-TLX questions. The participants assigned to the CACC conditions were also shown videos that explained the CACC concept.

Participants in all three experimental conditions were told the following:

"I am going to ask you to exit and reenter the freeway every fourth exit. I will give you verbal reminders to exit the freeway. There will be orange construction barrels blocking the other exit ramps. There will be other traffic on the freeway. The traffic is continuous and will not stop."

Each condition was given additional instructions.

The CACC with merge assist instructions were as follows:

1. Set the gap to Near.

2. Set the speed to 70 mi/h (112.65 km/h).

3. You will control steering—follow the car in front.

4. The system will accelerate and brake.

    - You do not need to use your brake on the exit/entrance ramps.
    - You can take over control by pressing the accelerator or brake.
    - Pressing the brake disengages the CACC system.
    - If you need to take control, press ENGAGE as soon as possible.

The CACC without merge assist instructions were as follows:

1. Set the gap to "Near."

2. Set the speed to 70 mi/h (112.65 km/h).

3. You will control steering—follow the car in front.

4. The system will accelerate and brake in the CACC lane.

    - The system will turn off once you leave the CACC lane (i.e., take the exit ramp).
    - The CACC system will NOT control your speed while merging.
    - After you reenter traffic, you will need to engage the CACC system again.
    - You can take over control by pressing the accelerator or brake.
    - Pressing the brake disengages the CACC system.
    - If you need to take control, press ENGAGE as soon as possible.

The control condition instructions were as follows:

1. The speed limit is 70 mi/h (112.65 km/h).

2. Drive as you normally would.

Following the slideshow presentation, participants were fitted with the GSR sensor and seated in the simulator cab where the controls and displays were reviewed, and the instructions were repeated. While seated in the cab, participants were asked to complete the simulator sickness questionnaire (SSQ) to provide a symptoms baseline. Finally, the eye-tracking system was calibrated to the participants.

Next, participants were asked to complete a brief practice drive. During the practice drive, participants were asked to merge into the dedicated CACC lane. They were asked to accelerate and gently brake. This was followed by more aggressive accelerating and braking, which was designed to help participants understand the limits of the vehicle dynamics. Drivers also moved between the travel lane and the breakdown lane (to the left) to familiarize themselves with the steering system. Once comfortable with the speed and steering dynamics of the simulated vehicle, participants practiced exiting and entering the main dedicated travel lane with a left exit and entrance ramp.

If assigned to a CACC condition, participants were then asked to engage the CACC system. With no vehicles ahead, the CACC system accelerated to 120.70 km/h (75 mi/h) until it closed on a platoon of CACC vehicles traveling at 88.51 km/h (55 mi/h). The platoon traveled at 88.51 km/h (55 mi/h) for 2 min and then accelerated to 112.65 km/h (70 mi/h). This highlighted the ability of the cruise control system to follow at a specified distance, even when traffic slowed.

Participants in the control condition were asked to drive as they normally would. The other vehicles in the simulation performed similarly as they did in the CACC conditions; they drove at 88.51 km/h (55 mi/h) for 2 min and then accelerated to 112.65 km/h (70 mi/h). The platoon behaved in the same manner as for the CACC conditions.

After traveling in the platoon at 112.65 km/h (70 mi/h) for 2 min, the NASA-TLX was administered verbally to all participants. This administration was intended to further familiarize participants with the workload assessment tool. With the conclusion of the workload assessment, participants were asked to take the next available off-ramp and come to a complete stop.

After completion of the practice drive, participants were asked to exit the vehicle and complete the SSQ.

The experimental scenario began with the participant seated in the third vehicle of a platoon of four vehicles. Once the participant was ready to begin, the two vehicles in front of the participant accelerated and merged into the CACC lane and cruised at 112.65 km/h (70 mi/h). The two groups that drove with CACC engaged the system, and the participant's vehicle maintained a 1.1-s gap between it and the vehicle in front of it. Participants in the control condition were asked to drive as they normally would, with no specific instructions given about following distance.

Participants were verbally reminded to exit the travel lane and then reenter traffic at the appropriate ramps. As soon as the participants successfully merged into traffic in the dedicated lanes after the first (exit 4) and fourth (exit 16) ramps, the NASA-TLX was administered to assess workload during the merge event ("during the preceding minute or so"). The NASA-TLX was also administered as soon as exit 14 was passed. (Participants did not use this exit.) This administration was intended to assess workload during uneventful cruising in a CACC platoon (also described as during the last minute or so).

After exiting the simulator, participants were asked to complete a final SSQ, debriefed, and paid for their time.

Experimental Design

The primary between-group independent variable was the level of cruise control automation used throughout the scenario.

The three distinct participant groups were as follows:

- **Control**: The driver manually controlled the longitudinal speed/gap in dedicated travel lane. The driver manually controlled the longitudinal speed/gap throughout merge.
- **CACC without merge assist**: CACC controlled the longitudinal speed/gap in the dedicated travel lane. The driver manually controlled the longitudinal speed/gap throughout merge.
- **CACC with merge assist**: CACC controlled the longitudinal speed/gap in the dedicated travel lane. CACC controlled the longitudinal speed/gap throughout the merge.

In addition to workload, there was one additional within-subjects variable—driving period—with eight levels that were intended to distinguish the effects of CACC on driver behavior. The eight periods are described in table 1.

Table 1. Driving period descriptions.

Period	Description
1	15-s period ending 45 s prior to exit for first merge event.
2	15-s period beginning 45 s prior to completing the first merge.
3	15-s period ending 45 s prior to exit for second merge event.
4	15-s period beginning 45 s prior to completing the second merge.
5	15-s period ending 45 s prior to exit for third merge event.
6	15-s period beginning 45 s prior to completing the third merge.
7	15-s period ending 45 s prior to exit for fourth merge event.
8	15-s period beginning 55 s prior to completing the fourth merge.

Participants

Participants were 60 licensed drivers recruited from the Washington, DC, metropolitan area. In total, data from 12 participants were not used due to poor data quality or simulator failures; data from 48 participants were used in analysis. Participants were required to be at least 18 years old and were screened for susceptibility to motion and simulator sickness. Table 2 shows the age group and gender counts by treatment group for the participants who provided useable data. The mean age of the younger participants was 33.4 years (range 19.4 to 44.5 years). The mean age of the older participants was 56.6 years (range 46.5 to 77.9 years).

Table 2. Demographic breakdown of participants in experiment 2 by treatment group.

Condition	Younger Females	Younger Males	Older Females	Older Males	Total
Control	4	4	5	4	17
CACC without merge assist	4	4	4	4	16
CACC with merge assist	4	4	3	4	15
Total	12	12	12	12	48

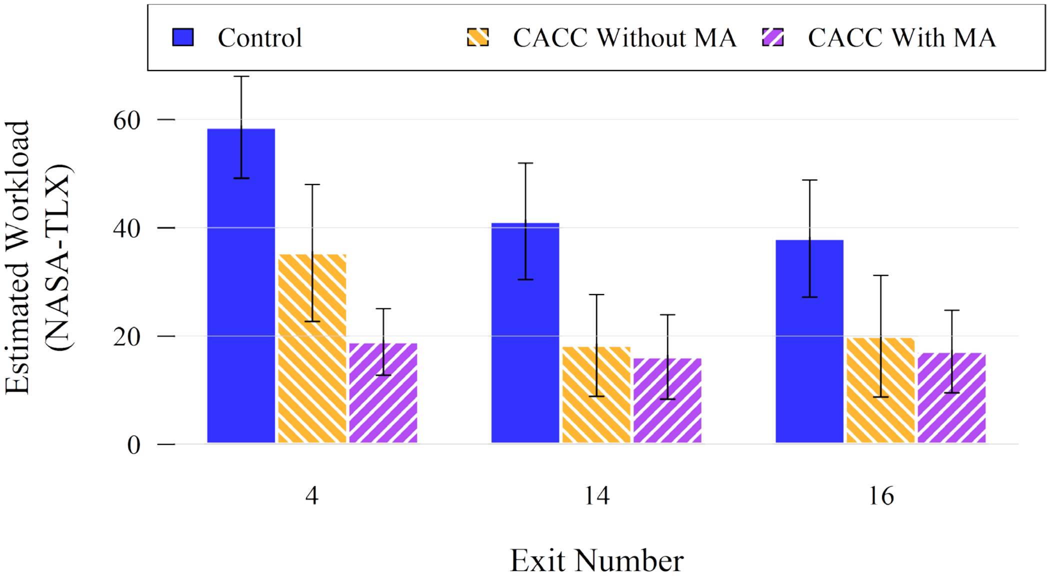
Participants were paid $80 for their participation, which lasted between 1.5 and 2 h.

CHAPTER 3. RESULTS

The results related to CACC and workload, physiological arousal, merge behavior, driving performance, distraction, and visual fixations are presented in this chapter.

WORKLOAD

The NASA-TLX was administered verbally at three points during the experiment: shortly after the first merge (exit 4), roughly halfway between the third and fourth merges (exit 14), and shortly after the fourth merge (exit 16). The effects of CACC and longitudinal assistance on workload were tested using generalized estimating equations (GEEs); normal response distribution, identity link function) with location as a repeated measure and experimental treatment condition as the between-group factor of interest. Resulting mean estimates with 95-percent confidence intervals for each condition and location are shown in figure 1.



MA = Merge assist.

Figure 1. Graph. Estimated mean workload (NASA-TLX) by treatment group and location.

As expected, experimental treatment condition significantly affected workload as measured by the NASA-TLX ($\chi^2(2) = 32.76$, $p < 0.001$). The mean NASA-TLX value for the control condition ($M = 45.94$) was significantly greater than both the with CACC merge assist ($M = 17.40$) and without CACC merge assist groups ($M = 24.52$; Dunnett-adjusted p-value, $p^D < 0.002$). The with and without groups were not significantly different from one another ($p^D > 0.05$). Location within the drive also significantly affected reported workload level ($\chi^2(2) = 23.84$, $p < 0.01$). The mean NASA-TLX value at exit 4 ($M = 37.63$) was significantly greater than both exit 14 ($M = 25.20$) and exit 16 ($M = 25.03$; $p^D < 0.002$). However, the mean NASA-TLX scores did not differ between exits 14 and 16. Participants reported higher workloads near the beginning of the drive than near the end of the drive despite the fact that the NASA-TLX was assessed during a straight away and after a merge.

As shown in figure 1, a significant location-by-condition interaction was found ($\chi^2(4) = 11.39$, $p = 0.02$). In order to more closely look at this interaction, each location was explored separately. Consistently across all three NASA-TLX assessment locations, condition significantly affected perceived workload; Exit 4 ($\chi^2(2) = 32.51$, $p < 0.001$), Exit 14 ($\chi^2(2) = 16.02$, $p = 0.003$), Exit 16 ($\chi^2(2) = 8.89$, $p = 0.012$). Within each of the assessments, the control condition had a significantly greater mean NASA-TLX score than the CACC with merge assist and CACC without merge assist groups (all $p^D < 0.05$). The interaction is the result of a difference in the first NASA-TLX assessment scores at exit 4. At this exit, the CACC without merge assist group has significantly greater workload scores than the CACC with merge assist group. This difference did not surface at the exit 14 and exit 16 assessments.

PHYSIOLOGICAL AROUSAL

The physiological measures of arousal assessed were GSR, eyelid opening, and pupil diameter. Each of these metrics naturally varied among participants, so raw values were converted to standardized *z*-scores. Data were sampled at approximately 120 Hz. (Some variation in sampling rate occurred as a result of occasional degraded signal quality.) The combined data sampling rate and length of each participant's driving session (30 to 35 min) generated an extremely large set of data. In order to better manage and grasp the datasets, the following analyses focus on the eight periods of interest identified in table 1.

GSR

GSR is generally considered to be sensitive to sympathetic nervous system arousal, and it is more sensitive to spikes in arousal than it is to gradual changes in arousal for longer periods of time. If merging is indeed stressful, higher levels of GSR should be seen for the merging periods (2, 4, 6, and 8) relative to the cruising periods (1, 3, 5, and 7). Furthermore, the drivers in the control condition should also exhibit greater levels of GSR relative to those who used the CACC system as a result of the arousal reducing effect of the automation.

Data from two participants in the control condition yielded GSR data that was not usable and, as a result, was eliminated from GSR analyses.

Mean-standardized GSR scores were analyzed using GEE (normal response distribution, identity link function, etc.). Resulting mean estimates with 95-percent confidence intervals for each condition and period are shown in figure 2.

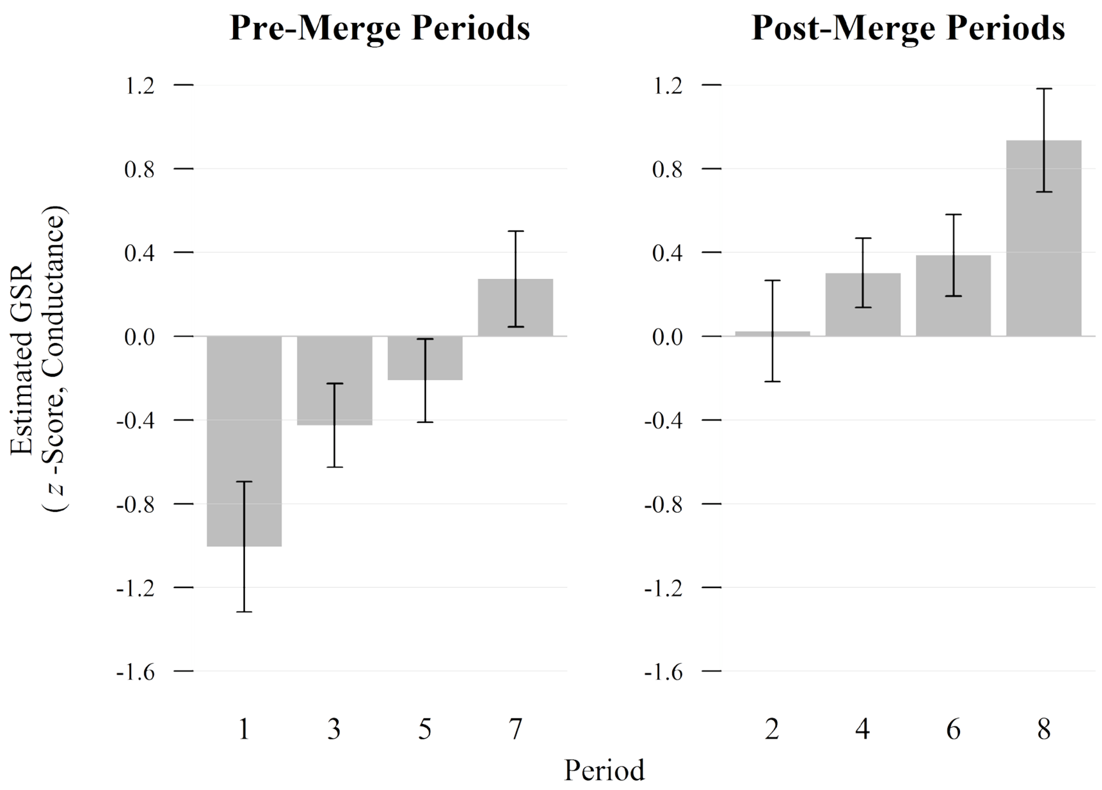


Figure 2. Graph. Estimated mean GSR (*z*-score, conductance) by period.

Time period in the drive significantly affected GSR ($\chi^2(7) = 139.16$, $p < 0.001$). As shown in figure 2, overall, GSR was significantly greater during merge periods than preceding cruise periods. In other words, participants were more aroused during the merge periods than during the cruise periods.

However, participant condition did not significantly affect mean GSR values ($\chi^2(2) = 1.49$, $p > 0.05$). That is, the presence of CACC did not significantly influence arousal as assessed by GSR. No significant interaction between participant condition and time period was found ($\chi^2(14) = 17.26$, $p > 0.05$).

Eyelid Opening

Eyelid opening is often associated with reduced alertness levels. In other words, as people become more relaxed or tired, eyelids tend to droop. If CACC reduces alertness, one might expect eyelid opening (measured in millimeters) to be smaller as the eyelids begin to droop with lower arousal levels (especially over time). As with GSR, the raw eyelid-opening measures were converted to *z*-scores. Eyelid-opening observations that the eye-tracking software classified with a quality rating less than 75 percent were excluded. This resulted in the exclusion of 39 percent of the eyelid-opening readings.

GEE (normal response distribution, identity link function, etc.) was used to assess the influence of experimental condition, period, and their interaction on eyelid opening. Overall, experimental condition did not significantly affect eyelid opening ($\chi^2(2) = 2.16$, $p > 0.05$), nor did the time period significantly influence eyelid opening ($\chi^2(7) = 6.02$, $p > 0.05$). The interaction between time period and condition was not significant ($\chi^2(14) = 15.28$, $p > 0.05$).

Pupil Diameter

Pupil diameter measurements for which the eye-tracking system reported less than 75 percent quality were excluded from the analysis. As with GSR and eyelid opening, each participant's pupil diameter observations across the eight 15-s periods were converted to *z*-scores. Once again, a GEE was used to assess the influence of experimental condition, period, and their interaction on pupil diameter. Resulting mean estimates with 95-percent confidence intervals for each condition and period are shown in figure 3.

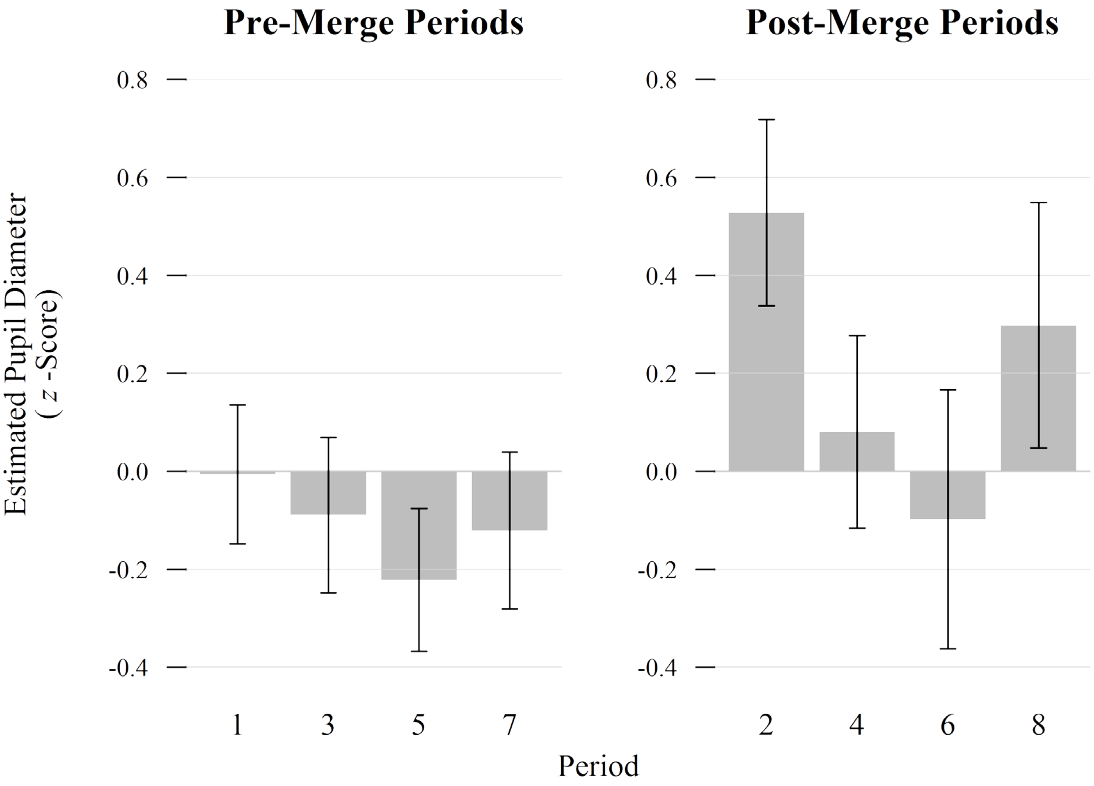


Figure 3. Graph. Estimated mean pupil diameter (*z*-score, conductance) by period.

Time period in the drive significantly affected pupil diameter ($\chi^2(7) = 44.12$, $p < 0.001$). Mean pupil diameter was significantly greater in period 2 than all other periods (except period 8; $p < 0.05$). This suggests that during the first merge of the experimental drive, participants were more alert despite the practice drive merging. In addition, the mean pupil diameter was significantly greater during period 8 than all other periods except periods 2 and 4 ($p < 0.05$). While this result may seem somewhat surprising, it may be an artifact of the experimental design. Participants were aware that this was the last merge and that the experimental session would soon be over. As such, participants may simply have been more alert in anticipation of the completion of the task.

The participant experimental condition did not significantly affect pupil diameter ($\chi^2(2) = 3.30$, $p > 0.05$). The interaction between time period and experimental condition was also not significant ($\chi^2(14) = 19.75$, $p > 0.05$).

DISTRACTION

The NASA-TLX assessment indicated that the CACC system with merge assistance reduced workload as compared with the control condition. Despite this, no differences were found in physiological arousal levels between the experimental groups. However, drivers can engage in activities to mitigate the tendency toward reduced arousal on long drives by engaging in arousal-stimulating secondary activities. In this experiment, participants were not discouraged from engaging in these activities. Care was also taken to avoid encouraging these activities, although participants were told that they could listen to the car radio or do what they normally do while driving.

To explore potential engagement in other arousal-increasing tasks, non-driving activities were recorded during two segments in the drive. The first segment was the 30 s prior to the beginning of the first exit maneuver (exit 4). The second segment was 30 s near the exit 13 overhead sign. Table 3 shows the non-driving activities participants engaged in at locations.

Table 3. The number of participants engaging in observable non-driving related activities by experimental condition group, combined across both observation periods.

Non-Driving-Related Activity	Control	With CACC Merge Assist	Without CACC Merge Assist
Listening to radio	7	8	9
Talking/singing	0	3	2
Listening to radio and talking	0	2	2
Moving hand away from steering wheel	9	3	4
Moving hand away from steering wheel and listening to radio	6	1	2
Talking and moving hands	0	0	2
Talking, moving hands, and listening to radio	0	0	1
Listening to radio, pushing buttons on radio, and moving hands away from steering wheel	0	1	0
Listening to radio and pushing buttons on radio	1	0	0
Total	**23**	**18**	**22**

As a result of the relatively small occurrences of the different types of potentially distracting non-driving activities, all were collapsed by group into a single number for analysis. Experimental condition did not significantly affect the number of non-driving related activities that participants engaged in ($\chi^2(2) = 1.10$, $p > 0.05$). Similarly no difference between the two observation periods was found ($\chi^2(1) = 0.62$, $p > 0.05$). Nor was the interaction between experimental condition and observation period significant ($\chi^2(2) = 1.63$, $p > 0.05$).

MERGE BEHAVIOR

Drivers' actions during each merge were closely monitored to detect differences in driver behavior both over time and as a result of experimental condition. These behaviors included merge success and position, gap selection, and the distance used to complete the merge. The following analyses are not based on the eight previously defined driving segments but rather on the merges themselves. The *beginning of each merge* was defined consistently across all participants as the moment when the driver passed a specified point on the on-ramp (shortly after passing through the signalized intersection); merge endings were defined as the moment when half of the driver's vehicle was laterally inside of the CACC platoon in the main lane of traffic.

Merge Success

As in the real world, a successful merge is one in which the driver avoids colliding with either vehicle defining the selected gap. As shown in table 4, several participants experienced a collision in the first merge attempt (despite the preceding practice drive), but the collision rate reduced with subsequent merges.

Table 4. Frequency of collisions by treatment group and merge number.

Condition	Merge 1	Merge 2	Merge 3	Merge 4
Control	9	2	2	1
CACC without	5	1	1	3
CACC with	0	0	0	0

It should be noted that a single participant in the CACC without merge assist group reengaged the CACC system earlier than instructed during the second and fourth merges. This participant turned on the CACC while still on the acceleration ramp. As a result, the participant did not appropriately adjust speed in order to find an appropriate gap and collided with other vehicles during both of these merges.

Because none of the drivers in the CACC with merge assist group collided with another vehicle, this group was excluded from the GEE model (binomial response distributions and logit link functions) analysis. That is, only the control and CACC without merge assist conditions were included. (It should be noted that if the drivers in the CACC with merge assist condition did not override the system or lose control of the vehicle, then it was not possible to collide with another vehicle in the simulation.) As one would expect, the analysis revealed no difference in collision rates between the control and CACC without merge assist groups. (Both groups were required to control speed and steering during the merge; $\chi^2(1) = 0.15$, $p > 0.05$.) However, the merges themselves did influence the likelihood of a collision, ($\chi^2(3) = 15.16$, $p = 0.002$). More specifically, participants were more likely to experience a crash during the first merge than in the follow three subsequent merges (Bonferroni correction for multiple comparisons, $p < .005$). It appears that with practice, drivers became more familiar with and better at merging into traffic in the simulator. One might expect similar patterns in the real world.

The interaction between participant condition and merge number was not significant in its influence on collisions during the merge ($\chi^2(3) = 2.38$, $p > 0.05$).

Merge Gap Position

Merge position describes the location where the selected gap drivers chose to insert themselves within the platoon. Here it is defined as the ratio between (1) the distance between the front bumper of the participant and the rear bumper of the vehicle ahead and (2) the distance between the rear bumper of the participant and the front bumper of the following vehicle. In other words, values closer to zero reflect merges closer to the front of the gap (i.e., closer to the vehicle ahead), and a value of 0.5 reflects a perfectly centered gap.

The algorithm used to control vehicle speed for those drivers in the CACC with merge assist was designed to place participant vehicles equally distant between two vehicles, allowing for a simple merge with only lateral adjustment in position.

GEE (normal response distribution and identity link function) modelling found a significant effect of treatment group ($\chi^2(2) = 11.29$, $p = 0.004$). Perhaps surprisingly, the participants in the control condition tended to merge in a similar location in the gap as those people driving in the CACC with merge assist group. In contrast, the CACC without merge assist group entered the gap significantly closer to the vehicle in front of the participant vehicle in the platoon than both the control and CACC with merge assist groups ($p < .005$).

Merge number did not significantly affect merge gap position ($\chi^2(3) = 5.49$, $p > 0.05$). The interaction between merge number and participant treatment condition was also not significant ($\chi^2(6) = 7.64$, $p = 0.27$). Figure 4 shows the mean merge gap ratios by condition.

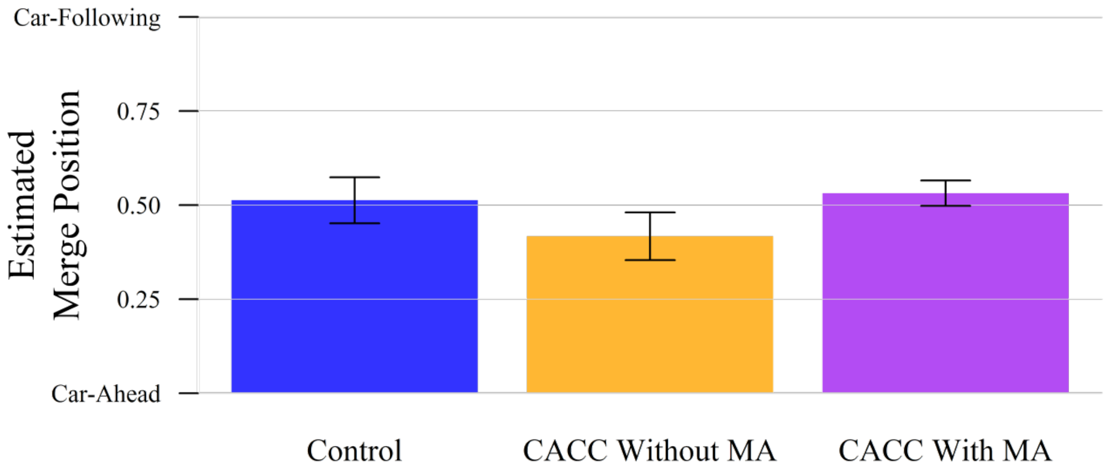


Figure 4. Graph. Estimated mean merge position by treatment group.

Gap Selection

All CACC drivers (both without and with longitudinal merge assistance) were presented the constant repeating 1.1-s merge gaps. Control drivers, on the other hand, were presented with the following repeating sequence of possible merge gaps (minimum and maximum underlined):

1. <u>0.7 s</u>.

2. 1.1 s.
3. <u>1.5 s</u>.
4. 0.9 s.
5. 1.4 s.
6. 1.2 s.
7. 0.8 s.
8. 1.0 s.
9. 1.3 s.

The platoon into which all drivers merged was moving at a nearly constant speed of 112.65 km/h (70 mi/h), meaning that a 0.1-s difference in merge gap is equivalent to 3.13 m (10.27 ft).

Gap selection among control drivers was modelled using GEE (normal response distribution and identity link function) as a function of merge number and prior gap (geographically, the gap behind the selected gap). The merge number did not affect the gap selected ($\chi^2(2) = 2.88$, $p = 0.24$), suggesting that participants did not modify their gap selection criteria after repeating the task several times. A prior gap was found to have a significant effect ($\chi^2(1) = 6.28$, $p = 0.01$), but this is believed to be an artifact of the experimental design: the model produced a negative coefficient on prior merge gap, indicating that an increase in the prior gap was associated with a decrease in the selected gap. However, the sequence of gaps presented is guaranteed to produce this decision in six of the nine possible combinations.

Table 5 shows the gaps presented to participants (repeated in this order) in the control group and the corresponding number of times it was selected. While the order in which the gaps were presented was not random, a chi-square revealed that no significant difference in the gap selected was found ($\chi^2(8) = 11.41$, $p > 0.05$). This indicates that participants were likely to enter the roadway at the gap presented at the bottom of the on-ramp rather than adjust speed and distance to find a more preferred or desirable gap.

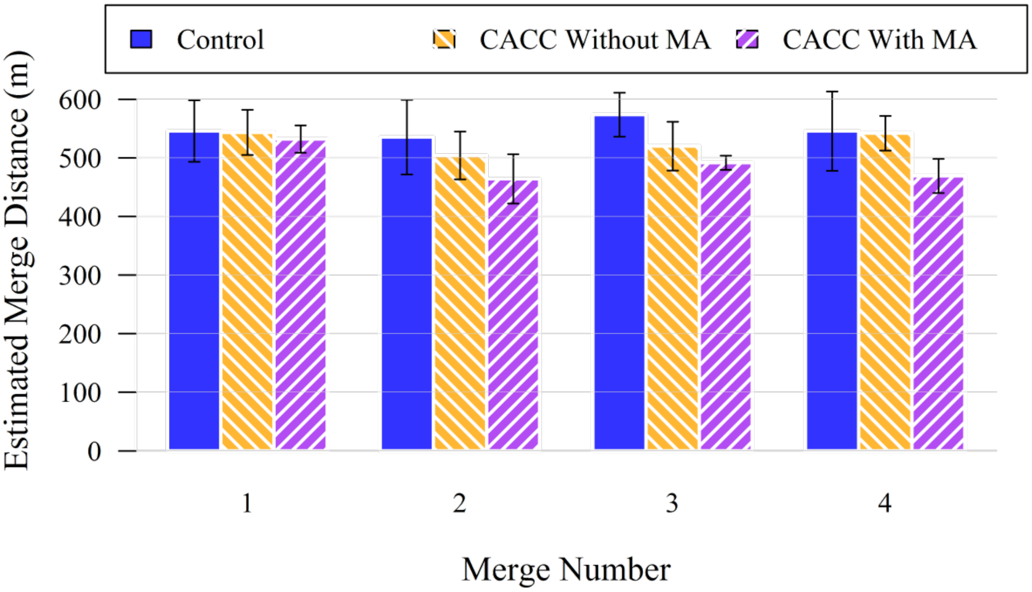
Table 5. Gaps presented to the control group and corresponding number of times selected.

Gap (s)	Number of Occurrences
0.7	4
1.1	6
1.5	9
0.9	5
1.4	8
1.2	15
0.8	8
1.0	8
1.3	5

Distance Used

The distance required to execute a merge may reflect the ease and/or comfort with which drivers make each merge. A short distance suggests that the driver quickly found and merged into a gap judged to be acceptable. However, a longer distance may suggest less comfort with gaps in the surrounding area or the need to adjust speed significantly to enter the traffic flow.

This distance was modelled with GEE (normal response distribution, identity link function) as a function of treatment group, merge number, and the interaction thereof. Resulting mean estimates with 95-percent confidence intervals for each condition and period are shown in figure 5.



1 m = 3.3 ft.

Figure 5. Graph. Estimated mean distance used to merge by merge number and experimental condition.

Participant condition significantly affected the distance used to complete a merge ($\chi^2(2) = 11.29$, $p = 0.004$). On average, both the control (*M* = 550.08 m (1804.72 ft)) and without merge assistance (*M* = 527.33 m (1730.09 ft)) used more distance to merge into the flow of traffic than the with merge assist group (*M* = 489.10 m (1604.66 ft)). Both groups that manually controlled speed used more of the ramp space than the CACC with merge assist group. This may have implications in terms of driver expectation of merge location and optimization of on-ramp throughput.

The distance used to complete the merge did not vary significantly based on merge number ($\chi^2(3) = 5.49$, $p > 0.05$). However, a significant interaction between experimental condition and merge number was found ($\chi^2(6) = 17.33$, $p = 0.008$). In order to further explore the interaction, distance was examined individually at each of the merges. No significant effect of participant condition was found at the first merge ($\chi^2(2) = 0.30$, $p > 0.05$) or the second merge ($\chi^2(2) = 3.26$, $p > 0.05$). However, significant differences between conditions were found at both the third ($\chi^2(2) = 11.40$, $p = 0.003$) and fourth ($\chi^2(2) = 6.09$ $p = 0.048$) merges. In the case of the third merge, the control group used significantly more distance to complete the merge than both the CACC with merge assist and CACC without merge assist groups (all $p^D < 0.05$). At the fourth merge, the control group and the CACC without merge assist groups performed similarly, both using significantly more distance to complete the merge than the CACC with merge assist drivers.

DRIVING PERFORMANCE

The measures of driving performance taken during this experiment were steering entropy and average absolute steering wheel torque. Unlike the physiological metrics, none of these required standardization. The following analyses focus on the previously defined periods of interest.

Steering Entropy

Steering entropy is a technique that captures corrective response and is frequently used to assess driver inattentiveness. One might expect higher levels of inattention in the groups with CACC because these drivers were not required to maintain speed and may have subsequently had more resources available to allocate to other tasks (including mind wandering).

Steering entropy was calculated for each subject within each 15-s cruising period (i.e., the periods where drivers were not expected to actively adjust steering to enter the platoon). Experimental condition was not found to significantly affect steering entropy values ($\chi^2(2) = 5.48$, $p > 0.05$). Further, neither period ($\chi^2(3) = 2.72$, $p > 0.05$) nor the interaction between period and experimental condition ($\chi^2(6) = 4.44$, $p > 0.05$) were significant.

VISUAL FIXATIONS

One way in which visual attention can be inferred is by examining where drivers are looking. Drivers in the CACC with merge assist condition did not need to control speed to successfully merge into the main travel lane. As a result, these drivers may not have felt the need to visually track traffic as closely as the control and CACC without merge assist conditions. This section explores the differences and similarities in glance patterns.

Dynamic regions of interest (ROIs) were established to capture the number and duration of visual fixations to the merge area (the area to the right of the participant's vehicle while merging into the CACC platoon, which is depicted in figure 6 as a red rectangle). Fixations were defined using eye-tracking software as consecutive gaze points falling within a radius of 1 percent of the projected screen within 300 ms (ending when new gaze points fall outside of an established radius for more than 120 ms).

Figure 6. Screenshots. Illustrated dynamic merge area ROI.

Two different approaches were used to examine glance behavior during merges. In the first approach, the number of fixations to the dynamic ROI was analyzed. In this case, participant condition did significantly influence the number of fixations to the ROI ($\chi^2(2) = 7.12$, $p = 0.028$). The control ($M = 2.65$) group had significantly more fixations to the ROI than the CACC with merge assist group ($M = 2.34$, $p^D = 0.024$). The CACC without group ($M = 2.41$) did not significantly differ from the CACC with group or the control group ($p^D > 0.05$).

In the second approach, the length of each merge was taken into consideration. Recall that significant differences in the amount of time utilized to complete the merges appeared across the different participant conditions. Subsequently, the total amount of time spent looking at the ROIs was divided by the total merge time, thus creating a proportion value. Participant condition did not significantly affect the proportion of time drivers spent looking at the dynamic ROI during the merge ($\chi^2(2) = 2.41$, $p > 0.05$). Similarly, neither the merge number ($\chi^2(3) = 0.05$, $p > 0.05$) nor the interaction between participant condition and merge number ($\chi^2(6) = 10.78$, $p > 0.05$) were significant.

TRUST IN THE CACC SYSTEM

Both the CACC with and without merge assist groups were required to accept some level of trust in the system. Recall that those participants in the CACC with merge assist group were not required to accelerate or brake at any point to successfully complete the drive. Of the drivers in this group, only one ever used their own speed controls to override the system. It is not clear, however, whether this person did not trust the system or simply did not understand the functionality of CACC. Throughout much of the drive, the participant manually controlled speed (by pressing the accelerator and keeping CACC engaged), spun out during the second merge, and did not reengage the system during the fourth merge.

Among participants in the without group, trust was examined during the cruising periods only because speed was manually controlled as drivers prepared to merge. Out of 16 participants in the without merge assist group, two engaged the accelerator pedal during a cruise period (one in period 1 and the other in period 7). However, in both cases, the pedal was used minimally (not necessarily in a manner indicative of distrust in the system) and was possibly the result of simple resting the foot on the pedal.

CHAPTER 4. DISCUSSION

The goal of this study was to explore drivers' abilities to merge with CACC platoons. Each participant completed four experimental merges in one of the following three different manners:

- Merging with non-CACC vehicle into a left dedicated lane without CACC platooning and varying vehicle gaps.
- Merging with CACC vehicle into the middle of a CACC platoon without speed assistance.
- Merging CACC vehicle into a CACC platoon with longitudinal speed assistance.

In addition to merging behavior and performance, workload and arousal were assessed.

As one would expect, perceived workload was significantly higher for the control condition than for both the CACC with and CACC without merge assist groups. This indicates that controlling speed does increase drivers' overall perceived workload. One might expect to reveal similar findings while using ACC and traditional cruise control dependent on traffic densities. It is often speculated that those people with lower perceived workload will engage in other activities to increase arousal (based on the Yerkes-Dodson Law).(4) However, no evidence was found that the different groups engaged in different or more non-driving tasks. Of course, it is reasonable to expect that the demand characteristics of the experimental environment dissuaded participants from participating in other activities given the social stigma associated with distracted driving. It remains possible that drivers may be more likely or willing to engage in non-driving activities under low perceived workload levels.

Despite a perceived increase in workload, no differences in physiological arousal between the different groups were found. The lack of difference between the different groups could be the result of two different causes. The first is that the task participants engaged in was simply too mundane to elicit increases in arousal. In other words, the driving task was so simple and routine that it did not increase arousal levels. The second possibility is that the equipment used to assess physiological arousal was not sensitive enough to capture subtle differences between the different participant groups.

Overall, participants were quite successful in merging into the constant platoon of vehicles. No drivers in the CACC with merge assist group collided with another vehicle while merging. However, as noted previously, if drivers in the CACC with merge assist condition did not override the system or lose control of the vehicle, then it was impossible to collide with another vehicle in the simulation because of the programming of the drive. In total, the control and CACC without merge assist groups experienced 24 collisions, over half (58 percent) of which occurred during the first merge. The improvement over time is likely the result of practice and experience (specifically, the experience of learning that the other vehicles do not respond quite like a real driver might). In the real world, as a driver, one might expect the vehicle behind you on a merging approach to slow and allow a more comfortable gap in order to complete the merge. Several of the participants that experienced a collision commented on the following vehicle not creating a larger gap. For example, one participant said “In my mind, I think he should have let me in,” while another said “Come on, guys…Let me in.” Taken together, it appears that the unanticipated behavior of the other traffic may have contributed more to the collisions that the actual abilities of the driver. With this in mind, it is it important to take other typical behavior that is seen in manual driving into account when designing road technology applications (e.g., other drivers creating gaps or slowing for emergency vehicles).

In sum, it appears that CACC with merge assist may increase the efficiency of drivers’ entering CACC platoons of vehicles. Drivers (with and without merge assistance) were willing to accept speed assistance in the simulated environment. Drivers also willingly entered gaps smaller than 1.1 s, showing that there may be a potential for smaller gaps to be used in a real-world setting.

ACKNOWLEDGEMENTS

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